

Strain data recorded in Xinjiang and their bearing on Tianshan's uplift/shortening and Tarim basin's rotation

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Abstract: Based on the continuous strain data recorded in Xinjiang since 1985, we discuss the mechanisms of Tianshan's uplift and Tarim basin's clockwise rotation. The results indicate: 1) The principal – compression directions in Tianshan are nearly NS, and their intersection angles with regional structures and mountains are nearly perpendicular, which is in accordance with Tianshan's uplift and crustal shortening. 2) The principal compressions around Tarim basin tend to facilitate the regional faults' left-lateral strike-slip movements and the basin's clockwise rotation. These phenomena of uplift/shortening and rotation are fundamentally the results of India plate's northward push on Euro-Asia plate, and the associated Pamir arc's rapid northward movement and regional blocks' interaction.

Key words: continuous borehole strain measurement; principal-compression direction; Tianshan uplift; NS crustal shortening; Tarim basin's clockwise rotation

1 Introduction

The mechanism of Tianshan's uplift and crustal shortening^[1] and Tarim basin's clockwise rotation has been a hot topic of discussion recently. Zhang^[2] et al. studied the deformation characteristics of Tianshan in terms of geological structure, and suggested that India plate's convergence with Euroasian plate was assimilated mainly by crustal thickening and eastward extrusion of Qinghai-Tibetan Plateau; they argued that some remaining energy might have passed through Tarim block and caused strong deformation of Tianshan and that Pamir plateau's extrusion towards north was also a cause for the deformation of Tianshan. In a study of crustal shortening of Tianshan, Molnar^[3] et al. suggested

that Tarim basin's clockwise rotation was an essential factor in causing Tianshan's deformation and crustal shortening. Having studied crustal deformation of Tianshan by using GPS data, Niu^[4] et al. suggested that the apparent deformational difference between eastern and western parts of Tianshan was caused by interaction between Pamir's northward extrusion and Tarim basin's clockwise rotation. However, Yang^[5] et al. thought that the deformation in Tianshan belt was probably caused by an "rolling" compaction effect. Some other researchers suggested that Pamir arc's extrusion in Tianshan's southern part alone was not enough to make the deformation; a southward extrusion of Siberia block in its northern part might be a factor also; the pair of shearing forces formed by this southward push and Pamir arc's northward push might have influenced Tianshan in an important way^[6].

In this study, we used a set of continuous strain data recorded at nine borehole strain stations in Xinjiang. Having calculated parameters of the horizontal strain field and analyzed the principal compressions' directions relative to regional geological settings, we discuss

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in this paper the mechanism of Tianshan's uplift and crustal shortening and Tarim basin's clockwise rotation.

2 The strain observation

The high-precision and high-sensitivity borehole strain-observation stations were first established in Wushi County of Xinjiang in 1984 and then in Urumqi, Korla, Shichang and Karamay et al. in 1990. The boreholes were more than 100 meters deep. The instruments were RZB - 1 type strainmeters produced by Institute of Crustal Dynamics, China Earthquake Administration. Each instrument consisted of 4 horizontal components intersecting at 45° angles. The sensitivity of the instrument was high (with a resolution of 10^{-10}), enough to record solid-earth tide^[7], and the dynamic range was big ($10^{-10} - 10^{-3}$ strain). Since the instruments were installed underground, disturbances by solar radiation, rainfall, ground vibration, and human-activities such as construction were much reduced.

After the disastrous Jiashi earthquake in 1998, nine sets of stressmeters were set up in Kax, Shache, Hetian, Bachu, Bole and Shihezi, et al. They were CZ - 1 type digital piezomagnetic stressmeters with moderate sensitivity. The instruments were put in boreholes at depths of 15 - 40 m in soil layers^[9]. These stations were located near faults for better response to earthquakes. Since the installation over 20 years ago, the instruments have recorded stress changes before several moderate and strong earthquakes in Xinjiang and surrounding areas, as reported in some previous studies^[10,11]. It would be viable for us to calculate stress fields by using this set of data^[12,13]. However, in this study, we chose to analyze the stable and continuous

data recorded at the previously mentioned nine stations.

3 Strain data and mechanism of Tianshan's uplift

When three or more strain components are observed, the parameters of the horizontal-stress field can be calculated by formula given in previously published papers^[14,15]. By using theoretical result in a paper^[16], we obtained the directions of horizontal principal compressions at the nine observation sites in Xinjiang.

The 2500 km long nearly EW - trending Tianshan mountains traverse the middle part of Asia, and about 1700 km of the mountains lie in Xinjiang. As shown in figure 1 and table 1, seven stations were located there. Among them, six showed compression and one tension (Shihezi station). The average direction of the observed principal compressions is $N15^\circ E$, reflecting a nearly NS squeeze of Tianshan region. Tianshan Mountains may be divided into North Tianshan and South Tianshan. Different sections of Tianshan have somewhat different directions and structural trends. The same is true for the observed principal compressions, as shown below.

3.1 North Tianshan area

Figure 1 shows the observed directions of principal compressions, which have three basic features:

1) They are consistently NNE trending. Bole station in the western part of North Tianshan is 400 km away from Urumqi station in the eastern part, but the directions of principal compressions were both NNE, ($N29^\circ E$ and $N38^\circ E$, respectively), the average being $N34^\circ E$.

Table 1 Directions of horizontal principal compressions and regional geologic structures

Satation	The time of data	The direction of structure(ψ)	The direction of principal compression stress(α)	ψ/α
Hetian	2001 - 01 - 2010 - 09	$N82^\circ W$	$N31^\circ E$	67°
Shache	2000 - 01 - 2009 - 08	$N42^\circ W$	$N11^\circ W$	31°
Kashgar	2000 - 01 - 2010 - 04	$N84^\circ E$	$N9^\circ W$	87°
Bachu	2005 - 01 - 2010 - 09	$N75^\circ E$	$N21^\circ E$	54°
Wushi	1985 - 01 - 1987 - 01	$N59^\circ E$	$N41^\circ W$	80°
Korla	1992 - 01 - 2008 - 12	$N65^\circ W$	$N53^\circ E$	62°
Bole	2005 - 01 - 2010 - 08	$N66^\circ W$	$N29^\circ E$	85°
Shihezi	2005 - 01 - 2010 - 09	$N78^\circ W$	$N4^\circ E$ (tensile)	82°
Urumqi	1992 - 01 - 2008 - 12	$N82^\circ W$	$N38^\circ E$	60°

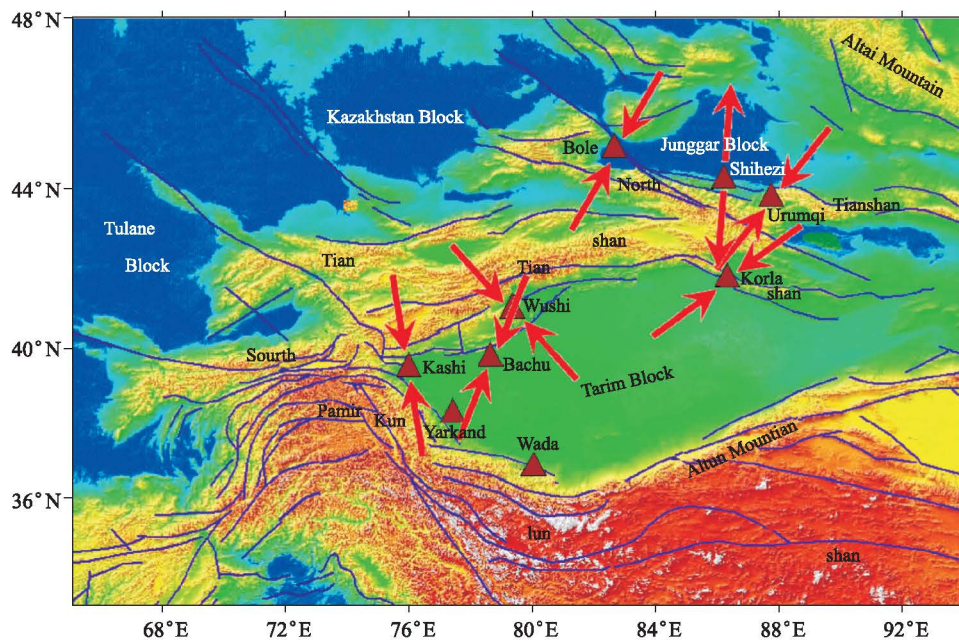


Figure 1 The observed directions of principal compressions in Tianshan

2) They are basically perpendicular to tectonic structures. To the north of Bole is the large right-lateral reversal strike-slip Boluokenu fault, which begins in Kazakhstan in the west and crosses Alashan, Jinghe, Kumishi, before reaching Tianshan^[17]; it cuts deeply into the lithosphere. The orientation of the fault near Bole station is $N66^{\circ}W$. Thus its intersection angle with the observed direction of principal compression at Bole is 85° , basically perpendicular. This feature is favorable to the fault's up-thrusting activity.

Urumqi station is located at the eastern end of Junggar south edge fault, which is a large regional fault in North Tianshan. It is 245 km long, spanning $N70^{\circ} - 80^{\circ}W$, and cuts into lower crust. This reversed fault, inclines to the south with a dip angle of $45^{\circ} - 75^{\circ}$ ^[18] and lies in $N82^{\circ}W$ direction near Urumqi. Since the observed direction of principal compression is $N38^{\circ}E$, the cross angle between them is 60° . Urumqi station is also located in the west wing of Bogda reflex arc oriented in $N56^{\circ}E$, which crosses the compression direction at an angle of 18° , favoring left-lateral strike-slip movement of this fault. A geologic survey of the fault planes near Urumqi showed that there were left-lateral reversal strike-slip and left-lateral strike-slip striations^[19]. This shows that the fault has been in mainly left-lateral strike-slip movement for about ten thousand years. Thus the direction of principal compression at

Urumqi station is mainly controlled by the large regional stress field in Tianshan tectonic belt, and influenced also by some small local stress field. The observed principal-compression favors Bogda reflex arc's northward protrusion. The Junggar south edge fault's westward movement is in accordance with Tianshan's uplifting and NS crustal shortening, but it is not in keeping with the anticlockwise rotation of Junggar basin^[5]. Geodetic-leveling data over the past 50 years shows that the vertical deformation-gradient lines in North Tianshan are oriented in NWW direction, and the amplitude of deformation is the largest in China mainland^[20]. This tends to verify the effect of the observed principal compression in NNE direction.

3) Their crossing angles with North Tianshan Mountain's direction of $N75^{\circ}W$ are bigger, averaging 71° . The crossing angle is 76° at Bole (where the principal-compression direction is $N29^{\circ}E$) in the western part of the mountain; it is 67° at Urumqi ($N38^{\circ}E$) in the middle part. Regional faults parallel with the mountain are thrust and overthrust showing the effect of the NNE compression, which is basically perpendicular to the direction of the mountain. The regional folds are close or even reversed, and strata are superposed. All these features indicate a continuing activity of Tianshan's ascension and crustal shortening.

3.2 South Tianshan area

1) The eastern part

In the eastern part of South Tianshan, there was only Korla station in operation; the direction of its principal compression is $N53^{\circ}E$, which crosses the $N65^{\circ}W$ direction of the chief structure in this area, Tiemenguan fault, at an angle of 62° . South Tianshan's direction turns from NEE to NWW near $E84^{\circ}$. The observed compression is in a direction helpful for the fault's reversed left-lateral strike-slip movement and for the mountain's uplift and crustal shortening.

2) The western part

In the western part of South Tianshan, there were three strain stations. This is where Tianshan, Kunlun Mountain and Tarim basin converge, and it has a special structural and complex stress environment. As a region showing NNW and NW compression, its features are obviously different from the eastern part, where NNE and NE compressions are shown.

(1) Kax station

Kax station is located in the border zone between the top of Pamir arc and Tianshan. Pamir arc is moving northwardly at a rate of more than $20 \text{ mm/a}^{[21]}$, and thus has a large northward-squeezing effect on Tianshan. The observed principal – compression direction here is $N9^{\circ}W$ and the structural direction is nearly EW ($N84^{\circ}E$), with a crossing angle of 87° , which is basically perpendicular. The direction of the mountain in Kax area is $N70^{\circ}E$, thus the crossing angle is 70° . This is consistent with this area's being squeezed by a nearly NS stress and its deformation of mountain uplifting and NS crustal shortening.

(2) Wushi station

The principal-compression direction at Wushi station is $N41^{\circ}W$, the only northwestwardly oriented squeezing stress observed in Xinjiang. This result is fairly consistent with the direction of $N53.23^{\circ}W$ measured in 1982^[22]. The observed direction of principal compression has a crossing angle of 80° with a $N59^{\circ}E$ – striking Kuokesale fault that traverses the area north of Wushi station. The direction of South Tianshan in this area is $N75^{\circ}E$, at a crossing of 64° . Thus the observed compression favors the NEE squeezing deformation, mountain uplifting and NS crustal shortening.

(3) Bachu station

The principal-compression direction at Bachu station is $N21^{\circ}E$, which is, quite different from those at Wushi and Kashi. Bachu is located in the border area between South Tianshan and Tarim basin, where the influence of Tarim basin is greater. Compared with Kax, Bachu is farther from Pamir arc, and is therefore less affected by the arc. Compared with Wushi, the influence of stress activity in Tianshan is smaller. Kalpin fault in this region has a crossing angle of 54° with the measured principal-compression direction here. This angle favors the fault's up-thrust and left-lateral strike-slip movement, and Tian Shan's uplifting and NS crustal shortening.

In summary, the observed principal-compression directions in Tianshan have a wide distribution, being NNE, NE, and NNW-NW, respectively, in North Tianshan and eastern and western South Tianshan. Yet, they are all basically perpendicular to the directions of the local structural lines and mountains (87° , 80° , 85° at Kax, Wushi and Bole, respectively; 54° , 62° , 60° at Bachu, Korla, Urumqi, respectively,). This result of many years' continuous strain measurement is in accordance with the mechanism of uplifting and NS crustal shortening in Tianshan region.

4 Strain data and mechanism of Tarim basin's clockwise rotation

Tarim basin is approximately rhomboid shaped. There were strain stations located at every side, except the southeast. Following is a description of the observed principal-compression directions at these stations and, their bearings on Tarim basin's clockwise rotation.

1) Southwest side

Two strain stations were located in the southwestern edge of Tarim basin; they showed different principal-compression directions. Shache station was in the middle of the edge (Fig. 2). Its principal-compression direction is $N11^{\circ}W$, intersecting at a 31° angle with the regional faults' direction of $N42^{\circ}W$ in the northeast of Pamir arc. This stress state basically reflects Pamir arc northward squeezing, which produced the right-lateral strike-slip movement along the faults. Possibly due to Pamir arc's fast movement, the observed northward

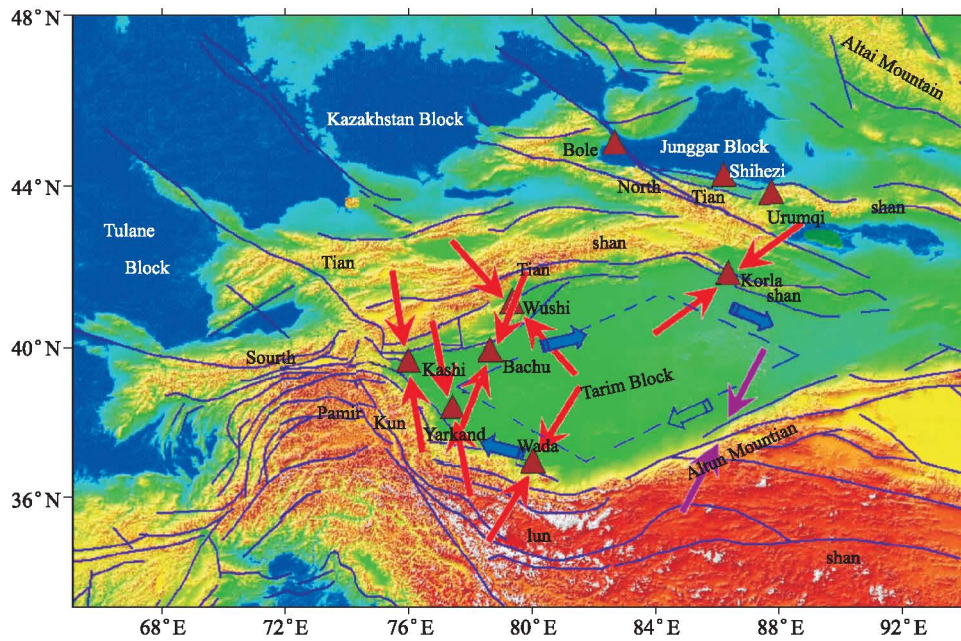


Figure 2 Observed principal – compression directions around Tarim block

velocity at Shache was over $20 \text{ mm/a}^{[21]}$, which is faster than the eastern part of Tarim basin, and is thus helpful for Tarim basin's clockwise rotation.

Hetian was located on the east side of Tarim basin's southwestern edge. Its principle-compression direction was $N31^\circ E$, which intersects the buried structure's strike of $N82^\circ W$ at a 67° angle. Probably because of this stress condition, the local faults show reversed left-lateral strike-slip movements (Fig. 3 (a)), which signifies not only the mountains' uplifting but also their NWW movement at Tarim basin side relative to the SEE movement at Kunlun Mountain side; this supports the viewpoint of Tarim basin's clockwise rotation.

Hetian is located at the eastern end of the west side of Kunlun structure belt and is near the west end of the large Altun left-lateral strike-slip fault. Its principle-compression direction is influenced not only by the stress field of West Kunlun structure belt, but also or, even more, by that of the Altun faults belt. The principle-compression direction of Altun faults belt is $N27^\circ E^{[23]}$, which is only 4° different from the observed $N31^\circ E$, at Hetian station.

2) Northwest side

Three strain stations, Wushi, Bachu and Kashi, were located on the northwest side of Tarim basin. The data at Kashi showed by and large the characteristics of Pamir arc's northward squeeze on Tianshan. The data

at Wushi mainly represented the stress features of Tianshan. Bachu station was located in the northwest edge of Tarim basin, and its data more effectively represented the stress features of Tarim basin.

The intersection angle is 54° between the principle-compression direction ($N21^\circ E$) and the regional Kalpin fault's strike of $N75^\circ E$ (Fig. 3 (b)). This result is consistent with Kalpin fault's reversed left-lateral strike-slip movement and Tarim basin's clockwise rotation.

3) Northeast side

The principle-compression direction observed during 1992–2008 at Korla station on northeast side of Tarim basin is $N53^\circ E$, which intersect the regional Tiemen-guan fault's strike of $N65^\circ W$ at an angle of 62° . (Fig. 3 (c)). This result is consistent with the fault's reversed left-lateral strike-slip movement and Tarim basin's clockwise rotation.

4) Southeast side

Although there was no strain station located on southeast of Tarim basin, it is well known that the large Altun fault is left-laterally strike-slipping at a speed of 9 mm/a currently^[24] (Fig. 3 (d)). This movement is again consistent with Tarim basin's clockwise rotation.

Thus the stress features on all four sides of Tarim basin are consistent with Tarim basin's clockwise rotation.

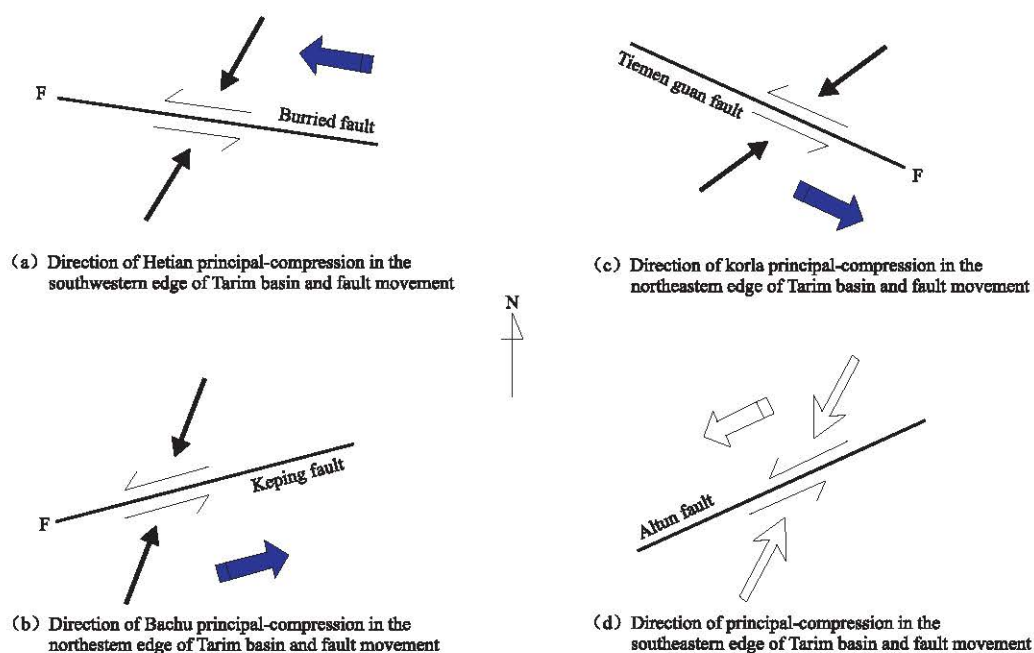


Figure 3 Directions of observed principal-compressions and local faults around Tarim basin

5 Summary of results and discussion

5.1 Results

In this paper, we have presented the strain data recorded continuously during a 26-year period at nine bore-hole stations, and attempted to use them to better understand the mechanisms of Tianshan uplift and crustal NS shortening, and Tarim basin's clockwise rotation. Several points are worth of noting:

1) Tianshan area is generally in a state of compression. Among seven stations there, six showed compressive stresses, but one (Shihezi) showed tensile stress. The directions of principal compressions are mainly NNE, with an average direction of N15°E.

2) The direction of principal compressions in Tianshan showed features of zonation. The direction of North Tianshan is NNE. The direction of the east part of South Tianshan is NE. The west part of South Tianshan is located in the joint belt of some tectonic units and the direction of stress there is more complex. Kax station is located in the joint area between Pamir arc and Tianshan, whose direction of principal-compression is nearly NNW. This reflects the stress state of Pamir arc's northward squeezing. Wushi station is located in the middle of Tianshan. The direction of principal compression is NW, which reflects the stress feature of

Tianshan region. Bachu station is near one side of Tarim basin where the direction of principal compression is NNE. It represents the stress condition in the northern edge of Tarim basin.

3) In Tianshan, the observed directions of principal compressions were all basically perpendicular to tectonic lines or across them with some big angles, with an average angle of 71°. This mechanical feature is helpful for the faults' thrusting and reverse-folding activities. Some investigation showed that multiple rows of reverse faults and folds exist in southern and northern foot of Tianshan. There are also active reverse faults and sag basins in the interior of Tianshan. These structures may have caused the strata to accommodate deposition and be thickened. They would facilitate Tianshan's uplift and NS crustal shortening.

4) The directions of principal compressions were approximately perpendicular to the extending direction of Tianshan, which is as a whole in latitudinal direction, though slightly different in different segments. The directions in North Tianshan, the west of South Tianshan, the east of South Tianshan are NWW, NEE, NWW, respectively. But no matter in which direction, the crossing angle between the direction of the observed principal compression and that of the mountain in every area was always more than 60°, indicating a squeezing effect that facilitates Tianshan's uplift and NS crustal shortening.

5) The directions of principal compressions in the southwest, the northwest and the northeast edges of Tarim basin were intersecting the local faults at acute angles. This facilitates the faults' left-lateral strike-slip movements. A previous research on Altun fault in the southeast edge of Tarim basin showed that the strike of Altun fault was $N65^{\circ}E$, and the direction of principal compression stress was $N27^{\circ}E$ ^[23]. The crossing angle between them is 38° . Currently Altun fault has a left-lateral strike-slip rate of 9 mm/a. Thus the faults on all four sides of Tarim basin are in left-lateral strike-slip movement, showing that the Tarim basin is indeed in clockwise rotation.

5.2 Discussion on the causes of Tianshan's uplift and Tarim basin's clockwise rotation.

On the basis of the observed large crossing angles between the nearly NS principal compressions and the nearly EW structures and of the circum-Tarim faults' upthrust and left-lateral strike-slip movements, we may understand the causes of Tianshan's uplift, NS crustal shortening and Tarim basin's clockwise rotation.

Firstly, the remote but fundamental effect of Indian plate's northward pushing on Eurasian plate has caused the whole Xinjiang region to move northwardly and led to the mountain uplift and NS crustal shortening. Secondly, Pamir arc's swift northward movement and its proximity to Southwest Tianshan, has produced strong squeeze on West Tianshan and thus helped the Tianshan's uplift, the NS crustal shortening and the different deformation intensities between Tianshan's west and east sides. The Pamir arc's northward squeezing on Tarim basin has caused a faster northward movement on its western part than eastern part, thus Tarim basin's clockwise rotation. Thirdly, some land blocks in Tarim, Junggar, Tulan and Kazakhstan have been interacting with one another, pushing strongly on their boundary belts and thus forming the large-scaled mountains in the region (Tianshan, Kunlun and Altai).

In conclusion, based on the continuous-strain observation, we have gained some better understanding of the mechanisms of Tianshan's uplift and Tarim basin's rotation. However, many problems remain to be studied. For example, why the stress condition was tensile at Shihezi station, but compressive at all other stations

in Xinjiang.

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